9.2 Orographic Factor, T/C

In HMR No. 49 (Hansen et al. 1977), the first approximation analysis of the orographic component to PMP was based on 100-yr 24-hr precipitation. A similar concept using a slightly different procedure was adopted for this study. Maps of 100-yr 24-hr precipitation (Miller et al. 1973) for the individual western states were used to form a ratio of total 100-yr to convergence component 100-yr rainfall, T/C, and it was assumed that this ratio is related to a ratio of similar parameters for PMP. The ratio of T/C for the 100-yr 24-hr rainfall can be used as a representative index of the orographic effects for the present study. One of the reasons for adapting this index is the degree of detail available in the 100-yr analyses. In hydrometeorological studies by the National Weather Service it has always been assumed that the level of detail in the PMP analysis is somewhat less than that for the 100-yr precipitation. If PMP is to have any detail in orographic regions, the 100-yr analysis must be sufficiently detailed.

The availability of the 100-yr 24-hr maps provides only part of the needed ratio, the total rainfall or numerator in the fraction, and it remains to determine how to obtain the convergence component, C. The rationale followed was that isopleths of the convergence component would exhibit a smooth, gradually varying geographic pattern. The gradients and general geographic variation would be somewhat similar to the FAFP component discussed in chapter 8. In part, support for this conclusion is found in the similarity of smooth PMP lines given for the United States east of the 105th Meridian (Schreiner and Riedel 1978), assumed to be convergence only PMP, and the smooth 100-yr 24-hr isopluvials of the "Rainfall Frequency Atlas of the United States" (Hershfield 1961), which are also assumed to be convergence only.

In the CD-103 region, it was proposed to look at the 100-yr precipitation analyses for the pertinent states with the intent of locating zones of least orographic effect, i.e., the least complex terrain. The approach followed was to assume that the 100-yr precipitation in these least-orographic zones was 100 percent convergence precipitation as in the Great Plains. These zones would then be tied together in some form of smooth analysis. It should be recognized that implicit in this approach is the fact that it did not allow for any consideration of negative orographic effects, zones where the convergence component was less than 100 percent. It was believed that any negative orographic effects would be small and have no significant affect on the study.

By isolating locations in which the convergence component was 100 percent of the 100-yr precipitation, it was possible to sketch a rough pattern of smooth contours through a major portion of the western United States that suggested how the analysis should appear. It was evident that the gradient of convergence 100-yr precipitation obtained by this method changed significantly for values less than 2.4 in. As a result, a relatively flat gradient (for isohyets <2.4 in.) was drawn over the intermountain region with an intense gradient from roughly the Continental Divide eastward to the western Plains. Figure 9.1 provides a schematic example of the final 100-yr convergence component analysis for New Mexico.

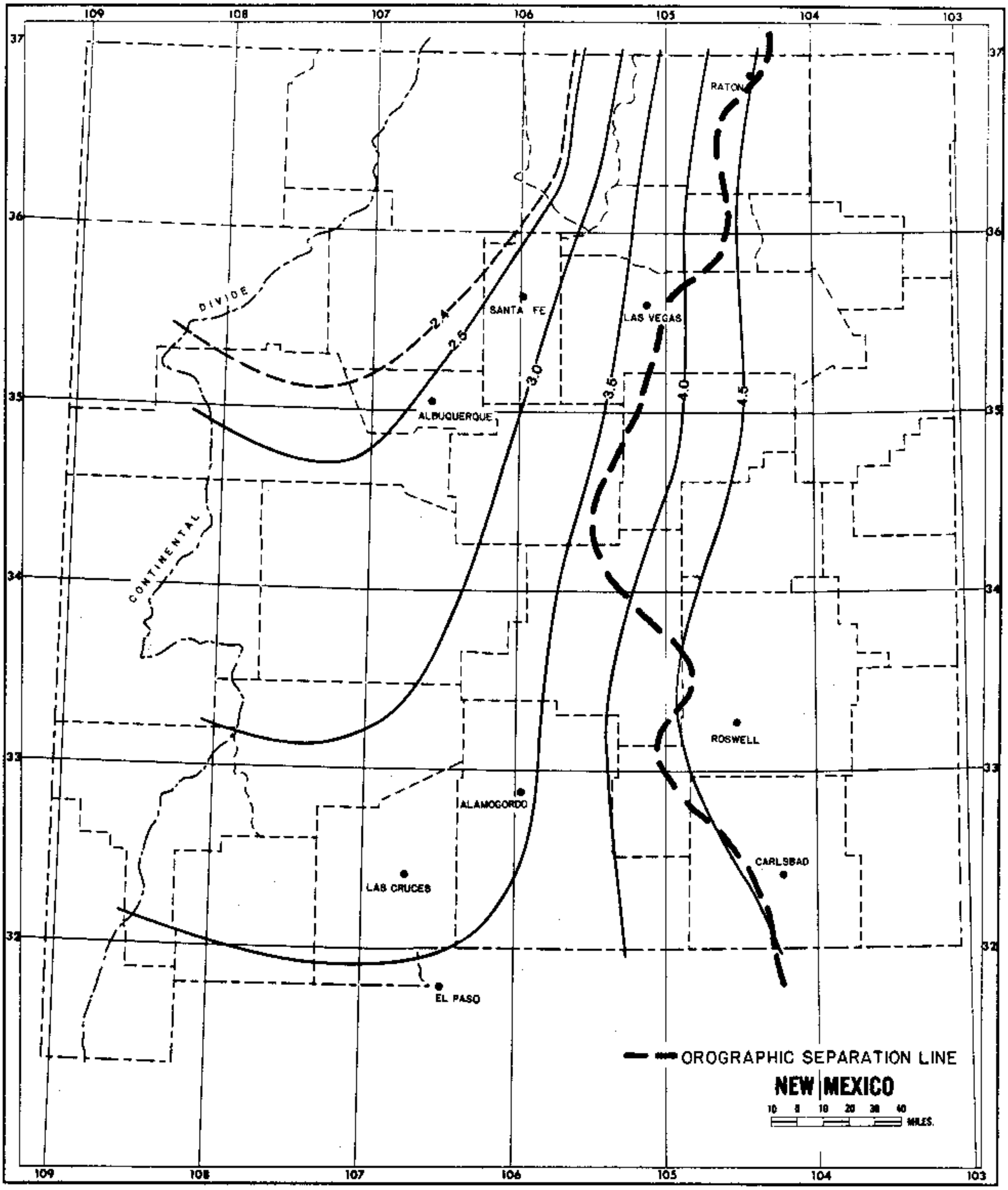


Figure 9.1.--Convergence 100-yr 24-hr rainfall (in.) for New Mexico between the Continental Divide and the orographic separation line.

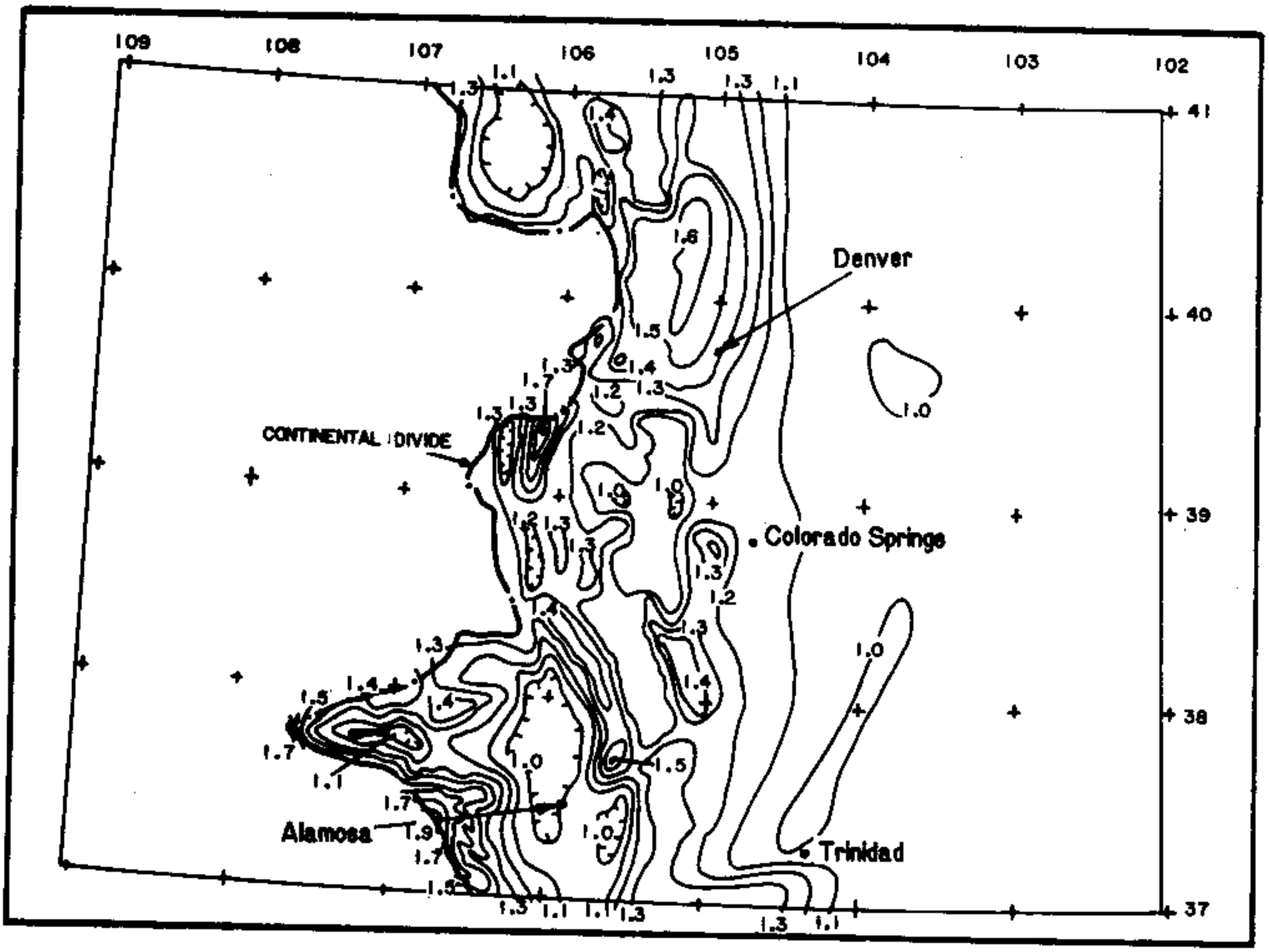


Figure 9.2.--T/C analysis for a portion of Colorado (10 mi^2 24 hr).

Although the evaluation of 100-yr convergence precipitation in figure 9.1 was done independently for the CD-103 study, a check was made against the working papers used in developing HMR No. 49, and it was found that with only minor adjustments to the analysis the patterns in the two studies would be compatible. The significance of this realization lies in the fact that although derived somewhat differently, the results lead to a comparable and consistent result. This tends to give confidence that the rationale proposed in HMR No. 49 and followed in this study can be applied over a broader region, and may have some universal applications, provided suitable 100-yr analyses are available.

Having obtained an analysis for the convergence component of the 100-yr precipitation, it was a relatively simple task to determine 100-yr values for T/C for as many points as believed necessary to establish the pattern for an analysis of these ratios. The analysis closely resembled the basic 100-yr 24-hr analyses and the ratio analysis was made simple by overlaying grid values on the original 100-yr maps, for guidance. The resulting ratio analyses are slightly smoothed by this process from the original level of 100-yr detail. Figure 9.2 shows a portion of the T/C analysis for Colorado as an example of results obtained by this procedure. In general, it was found that the orographic separation line defined in chapter 3 was in approximate agreement with the 1.1 ratio line on the

T/C analyses. This result was interpreted as providing independent support for the choice made in positioning this line. Ideally, it is expected that to the east of this separation line there would be little or no orographic influence, but practically, it can be expected that small effects (less than 10 percent) that are found in the T/C analysis are realistic in the rolling terrain of the eastern portion of the study region and acceptable in this study. The T/C map for extreme western Texas was developed by extrapolating relations from southern New Mexico, since this region is not covered by NOAA Atlas 2 (Miller et al. 1973).

9.3 Storm Intensity Factor, M

In initial application of the orographic factor to the convergence PMP represented by the FAFP, 24-hr 10-mi^2 PMP values in excess of 50 in. were estimated in parts of Wyoming and Montana. Analysis of the PMP values computed for a grid of points placed some local isopleth centers on lee slopes. These results implied a regionally varying adjustment was needed. This adjustment to T/C was resolved through consideration of the variation of dynamic forces within major storms as they apply throughout the region. The adjustment was termed the storm intensity factor, M, since it related the amount of precipitation that could be expected during the most intense precipitation period (within the duration under consideration) to the total amount of precipitation for that duration. This factor, thus, would vary with storm type.

In this study, the 24-hr period was selected as the base duration for determining PMP. It was necessary to determine the appropriate interval for the most intense period of this duration. The examination of major storms in this region indicates 6 hr was the appropriate shorter duration. The storm intensity factor was then defined as the ratio of rainfall in the maximum 6-hr period of the storm to the rainfall in the basic 24-hr period. M should be determined by dividing the FAFP for 6 hr by the FAFP for 24 hr. M was obtained by using total storm precipitation. This approximation assumes the FAFP component of the 6- and 24-hr amounts for 10 mi^2 are the same percentage of the total precipitation for those durations and area sizes. For these durations in this region, this is an acceptable approximation.

Major storms throughout the region were considered for guidance in determining the magnitude and distribution of this ratio. The most important storms gave the ratios shown in table 9.1. From these and other storm considerations, guidelines were established that permitted maps of M to be drawn for the region. One such guideline was that M was about 40 percent along the Continental Divide in Montana, Wyoming, and Colorado, increasing to about 50 percent along the Divide in New Mexico. This reflects the lower overall elevations along the Divide to the south, and the fact that more convective rain events are likely at these elevations in New Mexico, than in the north. Along the nonorographic zone at the eastern limit of the study region, the record of observed precipitation data suggested an M of 80-90 percent. A third major guideline was related to the gradient of maximum available moisture. Within the constraints just mentioned, the geographic variation of M was to be similar to the maximum persisting 12-hr 1000-mb dew points. Another guideline was based on the premise that longer duration rather than shorter duration precipitation is enhanced in those places of relatively high elevation or where a relatively strong elevation gradient occurs. In such places, the local modification acts to diminish the broadscale M. The opposite is assumed for places of low elevation and/or small elevation gradient. This interaction can also be thought of as an inverse relation between the probability that a dominating convective event occurs and

Table 9.1.--Ratios of 6-/24-hr precipitation for major storms used as guidance for M analysis

Storm Identification No.	Storm	Date	6-/24-hr ratio
75	Gibson Dam, MT	6/6-8/64	.40
47	Cherry Creek, CO	5/30-31/35	.93
101	Hale, CO	5/30-31/35	.74
112	Vic Pierce, TX	6/26-28/54	.60

the degree of orographic influence in the 100-yr frequency precipitation analyses. That is, when a 6-hr convective event dominates the total precipitation amount (high 6-/24-hr ratio), the orographic influence is most likely weak. Figure 9.3 is an example of the M analysis for Montana. This figure shows the analysis to be relatively smooth as expected when considering the availability of major storm data and knowledge of storm dynamics.

9.4 Computational Equation for Total PMP

The combining of the results of FAFP, T/C, and M was done through an empirical relation rooted in the assumption that total PMP was the product of the convergence component PMP and an orographic influence parameter, K:

$$\text{PMP} = (\text{FAFP})\ (\text{K}) \tag{9-1}$$

where K is a function of the orographic factor, T/C, and FAFP is the free atmospheric forced precipitation (sec. 7.2). The convergence component of PMP is represented as the sum of two parts representing the core, A (the maximum 6-hr amount) and B (the remaining 18-hr period), so that:

$$\text{PMP} = \text{AK}_1 + \text{BK}_2 \tag{9-2}$$

where A = (FAFP) (M)

B = (FAFP) (1-M)

K_1 = orographic factor during most intense 6-hr increment of 24-hr period

K_2 = orographic factor during remaining 18-hr of 24-hr period

Assuming K_2 to be equal to the T/C developed from the 100-yr 24-hr precipitation frequency values (sec. 9.2), K_1 can be represented by:

$$K_1 = 1 + P\ (T/C - 1) \text{ where } 0 \leq P \leq 1 \tag{9-3}$$

Equation 9-2 can then be rewritten as:

$$\text{PMP} = (\text{FAFP})\ \{M\ [1 + P\ (T/C - 1)]\} + (\text{FAFP})(1 - M)\ (T/C) \tag{9-4}$$

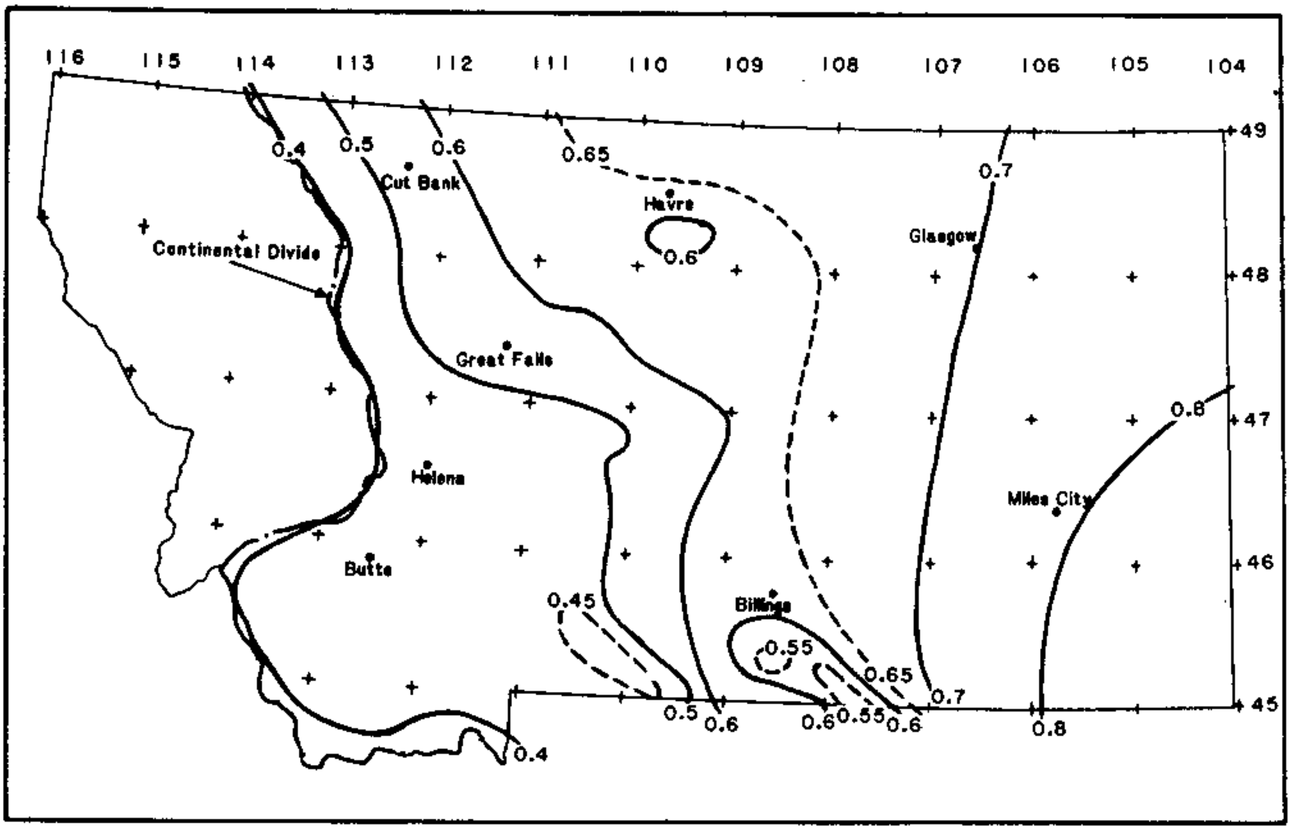


Figure 9.3.—M factor analysis for Montana (10 mi^2 24 hr).

To evaluate equation 9-4, a method for determining P must be developed. The value of P determines the percentage of T/C that is applied to the most intense or core portion of the 24-hr FAFP. It seemed reasonable for P to vary across the region, being most important in regions of strong orographic controls and least important in the Plains regions. This variation is in the opposite sense to the variation of M. Thus, a simple approximation was adopted:

$$P = 1 - M \tag{9-5}$$

Substituting equation 9-5 into equation 9-4 yields:

$$PMP = (FAFP)[M^2 (1 - T/C) + T/C] \tag{9-6}$$

where the expression in brackets represents the orographic influence parameter, K, in equation 9-1. It can be seen from equation 9-6 that as M and T/C increase, K increases; however, as shown in table 9.2, K increases faster at lower M than at higher M. Computations of PMP using equations 9-4 and 9-6 show that estimates of PMP are not sensitive to errors introduced by using the approximation of equation 9-5, when typical values of FAFP and T/C are used.

From equation 9-6, the effect of the orographic intensification factor decreases as the storm becomes more convective. In regions where more generally uniform rainfall prevails (smaller M), such as is characteristic of steep mountain slopes, T/C becomes increasingly important. Equation 9-6 has been used to compute total PMP for 10 mi^2 and the 24-hr duration in this study.

Table 9.2.—Values of orographic influence parameter, K, relative to variations in M and T/C

	T/C													
M	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3
.400	1.0	1.084	1.168	1.252	1.336	1.420	1.504	1.588	1.672	1.756	1.840	1.924	2.008	2.092
.425	1.0	1.082	1.164	1.246	1.328	1.410	1.492	1.574	1.656	1.737	1.819	1.901	1.983	2.065
.450	1.0	1.080	1.160	1.239	1.319	1.399	1.479	1.558	1.638	1.718	1.798	1.877	1.957	2.037
.475	1.0	1.077	1.155	1.232	1.310	1.387	1.465	1.542	1.620	1.697	1.774	1.852	1.929	2.007
.500	1.0	1.075	1.150	1.225	1.300	1.375	1.450	1.525	1.600	1.675	1.750	1.825	1.900	1.975
.525	1.0	1.072	1.145	1.217	1.290	1.362	1.435	1.507	1.580	1.652	1.724	1.797	1.869	1.942
.550	1.0	1.070	1.140	1.209	1.279	1.349	1.419	1.488	1.558	1.628	1.698	1.767	1.837	1.907
.575	1.0	1.067	1.134	1.201	1.268	1.335	1.402	1.469	1.536	1.602	1.669	1.736	1.803	1.870
.600	1.0	1.064	1.128	1.192	1.256	1.320	1.384	1.448	1.512	1.576	1.640	1.704	1.768	1.832
.625	1.0	1.061	1.122	1.183	1.244	1.305	1.366	1.427	1.488	1.548	1.609	1.670	1.731	1.792
.650	1.0	1.058	1.116	1.173	1.231	1.289	1.347	1.404	1.462	1.520	1.578	1.635	1.693	1.751
.675	1.0	1.054	1.109	1.163	1.218	1.272	1.327	1.381	1.436	1.490	1.544	1.599	1.653	1.708
.700	1.0	1.051	1.102	1.153	1.204	1.255	1.306	1.357	1.408	1.459	1.510	1.561	1.612	1.663
.725	1.0	1.047	1.095	1.142	1.190	1.237	1.285	1.332	1.380	1.427	1.474	1.522	1.569	1.617
.750	1.0	1.044	1.088	1.131	1.175	1.219	1.263	1.306	1.350	1.394	1.438	1.481	1.525	1.569
.775	1.0	1.040	1.080	1.120	1.160	1.200	1.240	1.280	1.320	1.359	1.399	1.439	1.479	1.519
.800	1.0	1.036	1.072	1.108	1.144	1.180	1.216	1.252	1.288	1.324	1.360	1.396	1.432	1.468
.825	1.0	1.032	1.064	1.096	1.128	1.160	1.192	1.224	1.256	1.287	1.319	1.351	1.383	1.415
.850	1.0	1.028	1.056	1.083	1.111	1.139	1.167	1.194	1.222	1.250	1.278	1.305	1.333	1.361
.875	1.0	1.023	1.047	1.070	1.094	1.117	1.141	1.164	1.188	1.211	1.234	1.258	1.281	1.305
.900	1.0	1.019	1.038	1.057	1.076	1.095	1.114	1.133	1.152	1.171	1.190	1.209	1.228	1.247

10. GENERALIZED 1-, 6-, 24-, AND 72-HR PMP MAPS

The general storm 24-hr 10-mi^2 PMP is developed from procedures discussed in the preceding chapters. The FAFP values (sec. 8.5) were adjusted for topographic effects by use of the orographic factor (T/C) (sec. 9.2) and the storm intensity factor (M) (sec. 9.3) in the computational equation developed in section 9.4. The 10-mi^2 general-storm PMP for the 6- and 72-hr durations were developed by applying durational ratios to the basic 24-hr PMP map. The 1-hr general-storm PMP map was developed using a 1-/6-hr ratio and the 6-hr PMP map. The development and analysis of these index maps is discussed in this chapter.

10.1 Duration Ratio Maps

Duration ratio maps were developed for 6-/24-, 72-/24-, and 1-/6-hr. The basic data used for these maps were:

1. Within-storm ratios for storms in the list of important storms (table 2.2).

2. Ratios computed for 100-yr return period amounts determined from NOAA Atlas 2 (Miller et al. 1973), Weather Bureau Technical Papers No. 40 (Hershfield 1961) or No. 49 (Miller 1964), or NOAA Technical Memorandum NWS HYDRO 35 (Frederick et al. 1977).

3. Ratios determined from maximum values of record for each duration for recording gage stations within the region.

4. Ratios based on PMP estimates for each duration from HMR No. 51 (Schreiner and Riedel 1978), HMR No. 52 (Hansen et al. 1982), HMR No. 49 (Hansen et al. 1977), and HMR No. 43 (U.S. Weather Bureau 1961).

5. Ratios between controlling storm values for each duration.

With these values available, analyses were prepared for each of the required ratios.

10.1.1 6-/24-hr Ratio Map

The first analysis was for the 6-/24-hr ratio. It was necessary to distinguish between the various data used to develop the analysis. Ratios based on 100-yr 24-hr amounts and on maximum-of-record amounts tend to be "among storm" values, i.e., different storms or storm types may control the 6- and 24-hr values. Other values, e.g., those from a major storm of record, are "within storm" ratios. The appropriate value to be used in the analysis must be based on the consideration of whether 6- and 24-hr PMP amounts would come from the same or different storms. Tests conducted during preparation of HMR No. 51 showed that for the region covered by that study, the PMP for all durations for a specified area size could come from the same storm. In this respect, interduration ratios from HMR No. 51 can be considered within-storm ratios. In this region, as in HMR No. 51, the premise was accepted that for a given area size, amounts for all durations between 1 and 72 hr can come from the same storm. Along the 103rd meridian, all within storm depth-duration ratios from extreme storm data agreed well with the ratios from HMR No. 51. This was to be expected, since the same storm types are controlling for all the various indices used in the study region and for HMR No. 51. At the western edge of the study region, there were some differences between ratios from HMR No. 43 and No. 49 and those within the CD-103 region, since there are greater differences in storm types east and west of the Continental Divide. In the CD-103 region, there appears to be more convective activity than west of the Continental Divide. This is particularly true northward from approximately 41°N. A primary criterion followed in the analysis of the 6-/24-hr ratio map, as well as the 72-/24- and 1-/6-hr ratio maps, was to maintain relatively smooth, linear gradients. Any change in the isoline gradient would have to be related to identifiable major topographic features. Another criterion developed from examination of the rainfall indices was that the lowest 6-/24-hr ratios were associated with the regions of steepest slopes. This is meteorologically reasonable since it is within these regions that the increased orographic effect would most tend to increase rainfall amounts beyond the maximum 6 hr.

HMR No. 55A further increased the rate at which the 6-/24-hr ratios decreased with increasing elevation. Where HMR No. 55 had shown only minor or little variation in ratios with elevation based on reasoning that increased convective potential at higher elevations compensated for moisture decrease, we now believe convective potential is much less significant at higher elevations in general storms. This has led us to reduce 6-/24-hr ratios on the order of 20 percent at the highest ridgelines. Somewhat similar gradients of ratios with elevation are found in the 6-/24-hr ratios along some of the west-facing slopes in HMR No. 43, a region that is also highly orographic in which overall convection is a minimum.

There is a tendency for the 6-/24-hr ratio to decrease from the southern portion of the study region northward toward Canada. While this overall general trend is present, there were local maxima where, for some distance, the opposite relation could be found.

10.1.2 1-/6-hr Ratio Map

The second map analyzed was for the 1-/6-hr ratio. Although the same data sources were used to develop all three ratio maps, little data were available for the 1-hr duration for the major observed storms within the region. As a first approximation, it was decided to use the pattern of the 6-/24-hr ratio. Most of the same considerations appropriate to the 6-/24-hr ratio map are appropriate for this ratio. An important additional consideration is the reduction in orographic controls. As the duration decreases, the effect of orography on extreme events tends to diminish. Thus, the 1-/6-hr ratio map (not shown) shows a lesser amount of variation than the corresponding 6-/24-hr ratio map. Since the 1-/6-hr ratios are controlled primarily by the dynamic atmospheric forces, the decrease in ratios across the OSL are less than for the 6-/24-hr ratio.

As in the 6-/24-hr ratio discussion, the 1-/6-hr ratios were also adjusted in HMR No. 55A. These ratios do not show much fall-off with elevation, as was also the case in HMR No. 55. In developing these ratios, consideration was given near the Continental Divide to 1- to 6-hr ratios in HMR's 43 and 49. Even with consideration of the ratios west of the Continental Divide, substantial general storm differences exist across the Divide. See discussion in section 13.6 to understand the consequences of these differences.

10.1.3 72-/24-hr Ratio Map

In developing the final ratio map for the 72-/24-hr duration, as with the 1-/6-hr ratio map, the 6-/24-hr ratio map was used as a first approximation to the isopleth pattern. However, in this case, the minima (maxima) in the 6-/24-hr ratio analysis became maxima (minima) in the 72-/24-hr ratio analysis (not shown). Also as a converse to the relation between topography and 1-hr amounts, the 72-hr values are more closely related to topographic variables than the 24-hr values. Therefore, somewhat greater variation in values can be expected on this ratio map. With these criteria and also using criteria similar to that discussed in relation to the 6-/24-hr ratio analysis, isolines were drawn for the data.

10.2 Computer Computation of Index PMP Maps

To develop a 24-hr 10-mi^2 PMP estimate, it was necessary to combine the values for the 3 parameters, FAFP (chapt. 7 and sec. 8.5), T/C (sec. 9.2) and M (sec. 9.3) through use of equation 9-6 (sec. 9.4):

$$\text{PMP} = \text{FAFP}\,[M^2(1 - T/C) + T/C] \qquad (9\text{-}6)$$

Computer facilities at the Bureau of Reclamation (USBR), Denver, were employed to rapidly and accurately process these data. Adequate delineation of the geographic variation of PMP required use of a dense grid over the CD-103 region. This was done by digitizing each of the individual parameter maps over the study region. Values from the maps were read into the computer by digitizing points along each isoline, interpolating to a rectilinear grid that approximated 17 by 18 units per geographic degree and then storing the interpolated values. Values were interpolated from these maps by use of the following equation:

$$G = \left(\sum_{i=1}^{n} \frac{X_i}{d_i^P}\right) \Bigg/ \left(\sum_{i=1}^{n} \frac{1}{d_i^P}\right) \qquad (10\text{-}1)$$

where:

- G = grid value;
- X_i = i-th digitized value;
- d_i = distance from grid point to location of i-th digitized value;
- P = selected power (weighting factor); and
- n = number of digitized points within specified area around grid point [specified area is defined in terms of number of grid units on each side (horizontal) or top and bottom (vertical) of the grid point in question].

In order to obtain the best set of representative grid-point values for each of the parameter maps, it was necessary to make several adjustments to the number of isolines on the basic maps or to the size area which was searched for isolines to use in equation 9-6 for regions where sharp changes in gradients occurred or where gradients were so lax that suitable digitizing points were not available to accurately define a grid-point value. First, additional isolines were drawn on the base maps such as those of figures 8.7, 9.2 and 9.3. This step added the required definition for determination of a grid value where a rather lax gradient existed. Second, changes to the specified area (range in space that was searched for digitized points in order to compute an individual grid value), as well as to the power factor P, were allowed in order to better calculate grid values in regions of steep or varying changes in map parameter isolines.

The specified area and power factor used for determining grid-point values for any particular analyzed map were typically represented as:

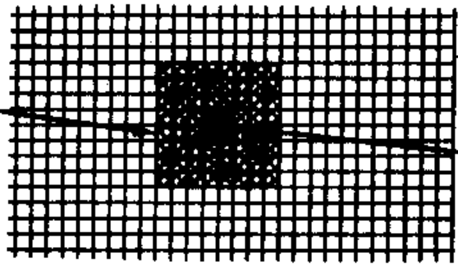
(4 X 4, 3.0)

where: 4 = Represents the number of horizontal, east-west, units searched;

4 = Represents the number of vertical, north-south, units searched; and

3.0 = Selected power factor.

A graphical representation of the above code is shown as:



Because of the numerous regions where steep changes in gradient, or centers of maxima/minima occurred on the T/C analysis, the grid spacing and power factor (weighting) used to determine a grid-point value were (1 X 1, 5.0). For all other parameter maps a criteria of (4 X 4, 3.0) was set.

Maps (referred to as number plots or numplots) that indicated gridded values of the three parameters, and various ratio maps, were prepared for each state. Another set of numplots was computed which combined the gridded data from the map representing each parameter in equation 9-6 to produce PMP values for 24 hr 10 mi^2. Finally, a machine analysis based on a linear interpolation of the 24-hr 10-mi^2 PMP grid-point data was prepared.

After the 24-hr 10-mi^2 maps were completed the 6-/24- and 72-/24-hr ratio maps, which had been digitized in a similar manner, were used to make the 6- and 72-hr 10-mi^2 PMP maps. In the development of these maps, the grid spacing and power factor (weighting) used were (4 X 4, 3.0). Numplots and machine analyses were made for the 6- and 72-hr 10-mi^2 PMP maps.

The 6-hr map and the 1-/6-hr ratio maps were used to develop the 1-hr 10-mi^2 PMP map. The procedure used and the types of products produced were the same as for the 6- and 72-hr maps.

10.3 Final Analysis of the 10-mi^2 General-Storm PMP Maps

The USBR machine analyses provided the basis for preparation of the final PMP maps. Each map was carefully reviewed and some changes were made. These changes were primarily to reflect topographic features, which in the judgment of the analysts were not adequately reflected in the machine analysis. In addition, the computer digitization, grid-point interpolation, and machine analysis procedures resulted in slightly irregular, "wavy" lines, particularly over the eastern plains portion of the study region. Although these could have been eliminated by a filter in the analysis program, it was decided to remove these by subjective smoothing during the review phase.

10.3.1 24-hr 10-mi^2 PMP Map

The 24-hr 10-mi^2 PMP is basic to all PMP estimates of this report. This duration was selected since more data are available for this duration than for shorter periods and use of amounts for this duration would minimize extrapolation to other durations. The initial estimates were made for the 10-mi^2 area because of the relative ease of relating differences in orographic effects between location. When considering larger area sizes, e.g., 1,000 mi^2, the shape and orientation of the 1,000-mi^2 area centered at a location could have a significant impact on the magnitude of the orographic effect.

The initial review of the computer analyzed 24-hr 10-mi^2 PMP map focused on the relative magnitude of the isohyetal centers on the more exposed slopes. Among the steepest slopes are those just northwest of Denver, from around Boulder northward to about Loveland. This is the approximate region of the Big Thompson storm (81) of July 31 - August 1, 1976. Other slopes nearly as steep occur west of Canon City, CO, southwest of Raton, NM, in the Big Horn and Wind River Ranges of Wyoming, and along the first upslopes of the Absaroka and Flathead Ranges in Montana.

The values shown on the 24-hr 10-mi^2 map at these locations were considered to be of the appropriate order of magnitude except near Boulder, CO. At this location, a small 37-in. center was present. Examination of the numplots showed only two grid points with values slightly in excess of 37 in. In this instance, as in other locations, centers supported by three or fewer grid-point amounts less than 0.5 in. larger than surrounding amounts were eliminated. Another modification in this region involved the 34-in. isohyet. The machine analysis showed this isohyet as discontinuous along the beginnings of the first upslopes. After examination of the numplots for all the input parameters and considering the terrain features, it was decided to make the 34-in. isohyet continuous from south of Pueblo, CO to about Fort Collins.

The only other region where significant changes from the computer-analyzed 24-hr 10-mi^2 PMP map were made was the Rio Grande Valley north of El Paso, TX. Considering the lower magnitude of southerly moist air inflow winds discussed in "Probable Maximum Precipitation for the Upper Rio Grande Valley," (U.S. Weather Bureau 1967) and the effect of the Guadalupe and Sacramento Mountains on tropical storm circulations, it was decided to reduce values west of the limit of first upslopes by 10 percent. This required some subjective smoothing across the crest lines of the first upslopes.

The final 24-hr 10-mi^2 PMP estimates are shown as plate III at the end of this report. Relative maxima are found in western Texas, northern New Mexico, near Boulder, Colorado, and near some of the first upslopes in Wyoming and Montana. Centers near the Big Horn and Wind River Mountains are 11 percent lower than the maximum values in western Texas and near Boulder of 36 in. These ranges are directly exposed to moisture bearing winds from the Gulf of Mexico as the moist air turns and moves westward north of a Low centered in central or southern Wyoming. Since both ranges are equally exposed to moisture bearing winds, equal values for those centers were considered appropriate. A slightly lower value, 30 in., was accepted for the Black Hills in South Dakota, because the terrain effects would be lessened by the limited lateral extent of the mountains. Maximum values in Montana are highest in the Absaroka Range in the south central portion of the state and along the Flathead Mountains near the Continental Divide. Maximum values on the Bear Paw and Little and Big Belt Mountains are less because of their limited areal extent. The Gravelly and Meridian Ranges and the Pioneer Mountains are located west of the limit of first upslopes, and maximum amounts are less for similar slopes and elevations in this region than on the first upslope region.

At the 24-hr duration, almost all moisture-maximized storm data are enveloped when the limits to maximization are considered. Just east of the study area, the moisture-maximized value of Hale, CO (101) exceeds the PMP in HMR No. 51 by 8 percent. The Cherry Creek, CO storm (47) of May 30-31, 1935 is a very extreme storm with a moisture maximization factor limited to 150 percent (sec. 5.4). With this limitation the PMP analysis equals the limited moisture-maximized amount. PMP for this location is still 50 percent larger than the observed amount.

The degree of detail shown in the isohyetal map is considered appropriate for variation of an event of PMP magnitude. The maps show less attention to topographic variation than mean annual precipitation or rainfall-frequency analyses. It is considered appropriate that, as the magnitude of the precipitation event increases, the scale of the topographic feature that would affect the precipitation pattern would also increase.

10.3.2 6-hr 10-mi^2 PMP Map (Revised)

The 6-hr 10-mi^2 PMP map is shown on plate II. This map was developed by applying the values from the 6-/24-hr ratio map (sec. 10.1.1) to the final values from the 24-hr 10-mi^2 PMP map over a dense grid of points.

The broad maximum defined by the 25-in. isohyet at 6 hr in Colorado and New Mexico matches well with the broad 32-in. maximum shown at 24 hr even though the 36- and 34-in. maxima at 24 hr have no counterparts at 6 hr. The 6-hr 26-in. center in western Texas is consistent with location of the comparable 24-hr center. In general, the axis of the "ridge" of maximum values at 6 hr is slightly downslope of the axis on the 24-hr analysis. The centers on the Big Horn and Wind River Ranges are not equal, as they were at 24 hr. This is attributable to the somewhat greater convective character of the storms in the eastern portion of the study region. For the same reason, the values on the Black Hills in South Dakota are larger than those in the Wind River Range and the Big Horn Range. In Montana, the maximum precipitation centers show a further decrease from the 6-hr amounts in Wyoming and Colorado. The lower values here reflect the changing characteristics of major storms as the distance from the moisture source increases and the orographic effects increase and the strong convective activity characteristic of the Great Plains decreases in importance. The relation between topographic features and the isohyetal pattern is less at the 6-hr duration than at the 24 hr, because the orographic effect is less pronounced when the most intense portion of the storm occurs (see discussion for M, sec. 9.3).

In central Colorado, the isohyetal analysis undercuts the moisture-maximized storm amount for the Cherry Creek storm (47). At this duration, the undercutting is 15 percent of the storm amount moisture maximized by the 150 percent limitation (see sec. 5.4). The observed amount is still enveloped by 28 percent. The Hale (101) and White Sands (82) moisture-maximized storms are undercut at 6 hr by 1 and 5 percent, respectively. The undercutting at White Sands was considered acceptable because of uncertainty in the proper 1- to 4-hr ratio and difficulty in assigning a moisture maximization factor to use for this storm.

Though specific tests similar to those done in HMR No. 51 have not been conducted, it is considered appropriate for the 6-hr general-storm amount to occur in the same storm as the 1-, 24-, and 72-hr amounts. The data shown in table 5.4 support this assumption, where data for eight storms provide the largest values for the various durations at any specific area size.

The maximum 6-hr value for small areas may not be the result of a general storm. At some locations, particularly in the orographic regions, for a PMP of less than 500 mi^2, it will be necessary to compute values from both the local- and general-storm criteria. Hydrologic tests will be required to see which of the two results will be most critical for any particular application.

10.3.3 1-hr 10-mi^2 PMP Map (Revised)

The 1-hr 10-mi^2 general-storm PMP map (plate I) was developed in the same manner as the map for the 6-hr duration. The 1- to 6-hr ratio map (sec. 10.1.2) formed the initial guidance. In addition, 1- to 24-hr ratio maps were drawn to provide guidance here. The correspondence with the terrain features follows the trend established with the 6-hr PMP map. Maximum centers again tend to be displaced slightly downslope from those on the 6-hr map. The shift in axis is somewhat lessened since the orographic effect had already been considerably diminished at the 6-hr duration. The smallest 1-hr values occur within regions where there is the most sheltering from direct moisture inflow. What was said of the 6-hr 25-in. isohyet in section 10.3.2 may also be said of the 15-in. isohyet at 1 hr. There is no center at 1 hr in western Texas corresponding to the centers indicated at 6 and 24 hr even though this same area is encompassed by a broad precipitation ridge at 1 hr. Throughout the study region, many of the other closed isohyetal centers can still be identified, but where the value within the closed isohyet on the 6-hr PMP map is not greatly different than the surrounding values a closed center generally no longer exists on the 1-hr map. An example of this can be seen in the northern Flathead Mountains in the vicinity of Gibson Dam, MT. In this region, a closed 14-in. isohyet was present on the 6-hr map, while at 1 hr only the slight indication of a ridge of higher values can be detected.

Four critical storms occur at 1 hr that control the level of 1-hr 10-mi^2 general-storm PMP: Buffalo Gap (72), Virsylvia (35), White Sands (82) and Big Thompson (81). The first of these storms occurred about 6 mi north of the United

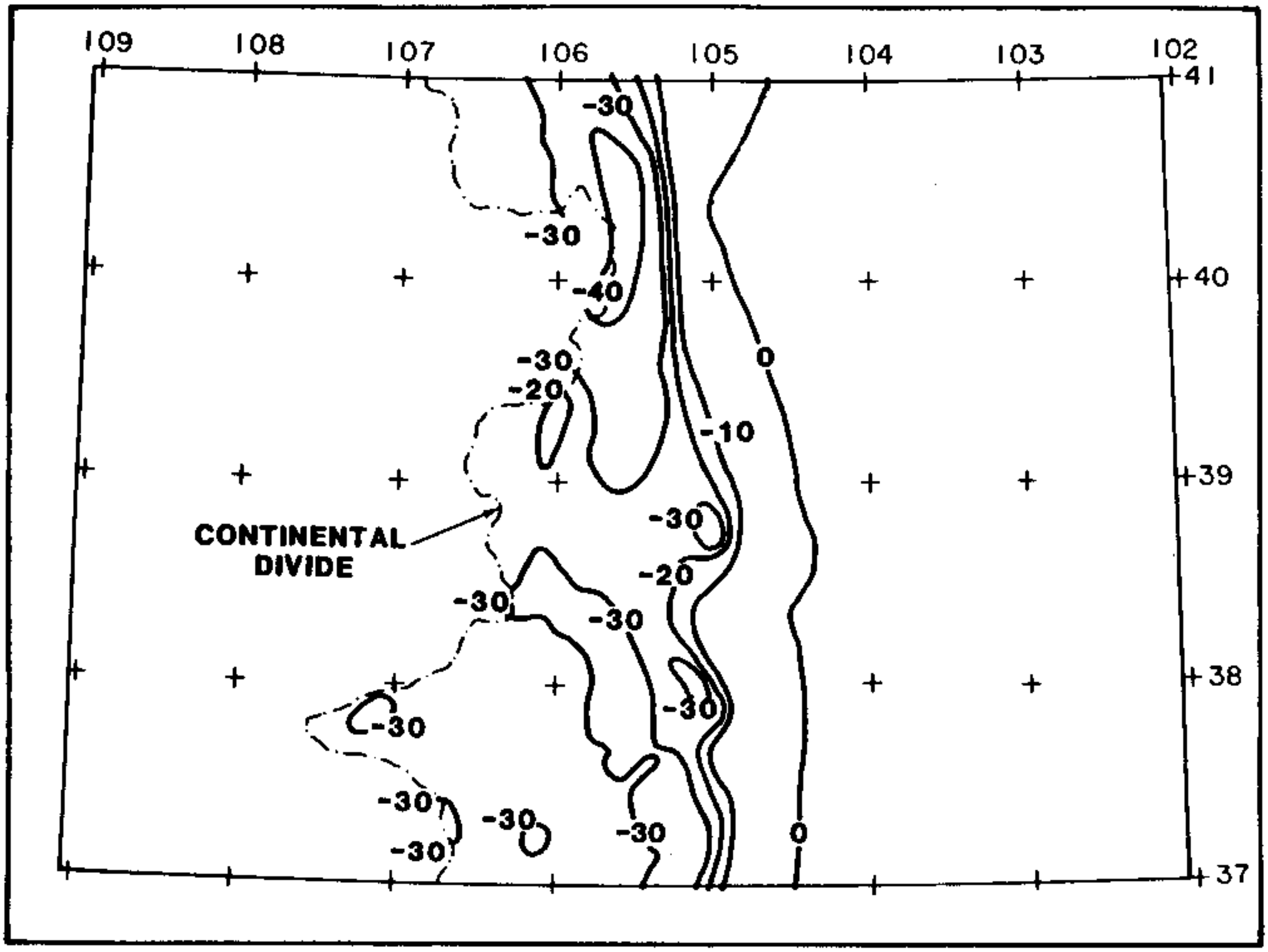


Figure 10.1.--Example of percentage change in 1-hr 10-mi^2 general-storm PMP index map for current study relative to that given in HMR No. 55 (1984), for Colorado. Considerable smoothing applied to example over detailed analysis.

States-Canada border. The observed 1-hr 10-mi^2 amount at Buffalo Gap of 7.0 in. was maximized in-place by 150 percent for moisture to obtain 10.5 in. The moisture-maximized value is enveloped by 6 percent in plate I. At the location of the Big Thompson storm, PMP from plate I envelops the 1-hr 10-mi^2 moisture-maximized value by 3 percent. Both the Virsylvia and White Sands moisture-maximized amounts are undercut in plate I by 8 percent. As noted for 6 hr, this degree of undercutting has been accepted since there is some uncertainty in the 1- to 4-hr ratios and the moisture maximization factor used to determine 1-hr values for these storms.

As with the 6-hr PMP estimates, the user needs to consider local-storm PMP values. The local-storm PMP estimates can be larger for small area sizes and may provide more critical hydrologic design criteria.

Figure 10.1 provides a representation (considerable smoothing applied) for Colorado of the percentage change resulting from the modifications made to the 1-hr 10-mi^2 general-storm PMP maps. Changes exceeding 40 percent are noted in the vicinity of the Continental Divide between 40 and 41°N latitude. In the detailed maps, somewhat smaller centers of 40 percent change occur at other high elevation locations in the Sangre de Cristo Mountains in Colorado and in the Wind River and Big Horn Mountains in Wyoming (not shown). This figure also shows that significant changes (>10 percent) for the most part are limited to the orographic portion of the study region, and generally increase with increasing elevation.

10.3.4 72-hr 10-mi^2 PMP Map

Plate IV provides the 72-hr 10-mi^2 general-storm PMP. These estimates were developed in the same manner as the 1- and 6-hr estimates. Values of the 72-/24-hr ratio (sec. 10.1.3) were determined for a dense grid (sec. 10.2) and applied to the 24-hr 10-mi^2 PMP estimates (sec. 10.3.1). A numplot and computer analysis were prepared as the initial step. The computer analysis formed the basis for the final 72-hr 10-mi^2 PMP map. The degree of correspondence between terrain features and the isohyets on the 72-hr map is somewhat greater than for the 24-hr map. This is to be expected since the terrain has a greater "fixing effect" on the lower intensities at the beginning and end of the storm than on the most intense 24-hr period. It also follows as a consequence of these considerations that the maximum centers on the 72-hr PMP map will tend to be displaced slightly upslope from those on the 24-hr map. The basic pattern on this map is similar to that shown on the 24-hr map. Increases over 24-hr amounts are greatest in the orographic regions.

11. DEPTH-AREA-DURATION RELATIONS

11.1 Introduction

In HMR No. 51, maps were prepared for several durations and area sizes. From this set of maps depth-area-duration (DAD) curves can be drawn to provide results for other area sizes and durations. The approach taken in this study is to provide DAD relations that are to be used in conjunction with the 10-mi^2 index maps to obtain PMP for other durations and area sizes. The DAD relations developed were based on depth-area relations for critical storms in and near the CD-103 region. Also, it was believed the complexities of the terrain would make it very difficult to follow consistently the procedure used to obtain 10-mi^2 PMP for all the necessary area sizes. As a result, the approach followed in this study is similar to that used in HMR No. 33, "Seasonal Variation of the Probable Maximum Precipitation - East of the 105th Meridian for areas from 10 to 1,000 Square Miles and Durations of 6, 12, 24, and 48 Hours" (Riedel et al. 1956), and in an "Interim Probable Maximum Precipitation Study" (National Weather Service 1980a, 1980b) for this region.

11.2 Data

The data used in development or verification of the DAD relations were taken from DAD summaries available for almost all storms on the list of storms important to developing PMP for the CD-103 region (table 2.2). These DAD summaries appear on the pertinent data sheet for storms reviewed by the Corps of Engineers (1945-), the Bureau of Reclamation, and the Hydrometeorological Branch, NWS. For easy access, summaries of the DAD information for the important major storms have been tabulated in Appendix B to this study.

11.3 Method

One of the first considerations in developing DAD relations is examination of how these results vary regionally. It would be convenient if there was no regional variation, and one set of relations applied everywhere. This is often the case for relatively small area studies, e.g., individual drainage estimates or generalized estimates for moderate size river basins. However, over as large a region as the CD-103, it is more realistic to expect that the DAD relations would have some regional variation. It is not necessary to develop a depth-area-duration relation for every location since there is some local homogeneity. Terrain and storm type have a predominant effect on DAD relations. Therefore, a finite number of additional subdivisions should be adequate for the CD-103 region.

11.3.1 Topographic Subdivisions

Initial subdivision followed the terrain classification system described in chapter 3. To recap here, there was a basic division between orographic and nonorographic regions as denoted by the orographic separation line. Within the orographic portion of the region, further division resulted in first upslopes (or orographic), secondary sheltered orographic, and sheltered least orographic subdivisions (fig. 3.2).

For HMR No. 51, studies were made to determine the longitudinal variation of storm magnitude. This study supported a greater decrease in precipitation with increasing area size and with increasing longitude. Presumably, this is due to the difficulty of sustaining large area moisture inflows as the western edge of that study (105th meridian) is approached. This suggests that DAD relations in the nonorographic regions west of the HMR No. 51 region should decrease with increasing area size at an even faster rate than they do within the HMR No. 51 region. DAD relations in HMR No. 51 are viewed as an important guide to how larger area data relate to 10-mi^2 PMP over the eastern portion of the study region. The fact that they are the result of storm envelopments from a much larger sample of available storms is significant.

As a result of the concepts stated above, an additional subdivision was developed in the nonorographic portion of the CD-103 region in which DAD relations have greater slopes (more rapid decrease with area) than those in HMR No. 51. In figure 3.2, terrain features were used to distinguish between subdivisions. For the new subdivision, which is a minimum nonorographic region, the western boundary is the OSL, and there was no such basis to identify or limit the eastern bound. The subdivision is limited on the east by a line placed according to where the uniform gradient of isopleths of PMP extending from HMR No. 51 changes direction on the index PMP maps for this study. This eastern boundary is somewhat arbitrary, but is considered reasonable. The dotted line in figure 11.1 shows the location of the eastern limit to this subdivision.

11.3.2 River Basin Subregions

The results of the subdivision analysis shown in figure 3.2 provide a variation that is essentially east-west. Considering these variations together with the fact that the 10-mi^2 PMP index maps were based on major controlling storms that are distributed generally north-south, it was concluded that additional divisions were needed for DAD relations. Initially, the concern for controlling storms led to a division between extratropical and tropical storms (see discussion in

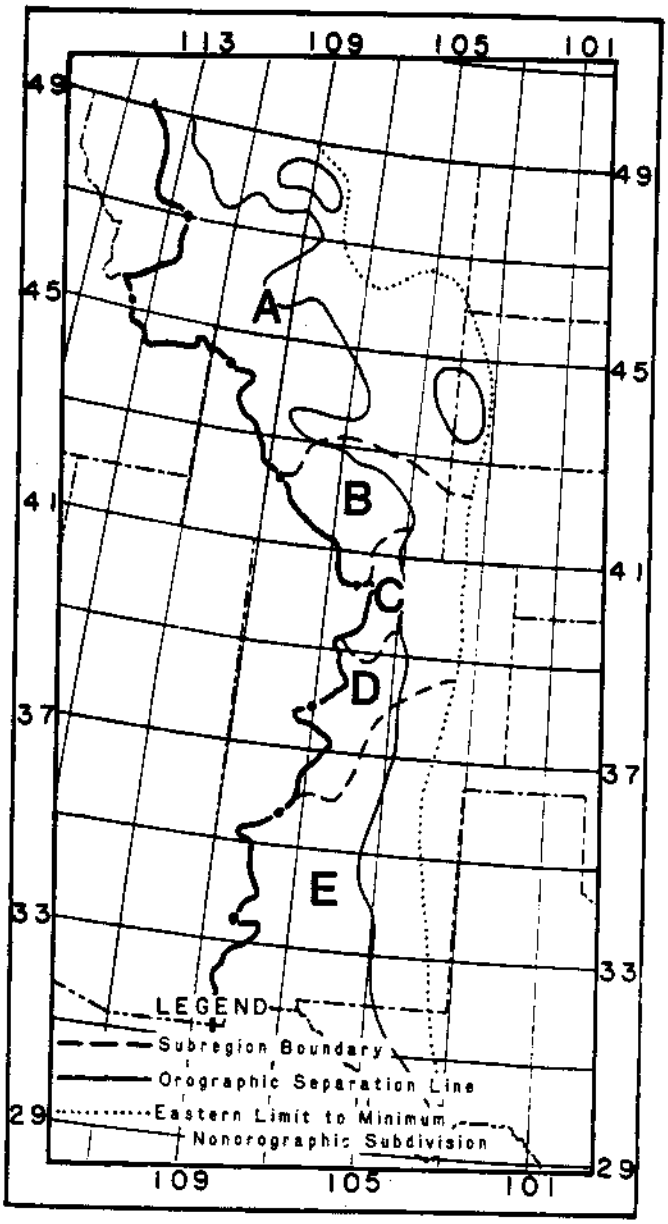


Figure 11.1.--Location of minimum nonorographic subdivision and five subregions in the CD-103 region.

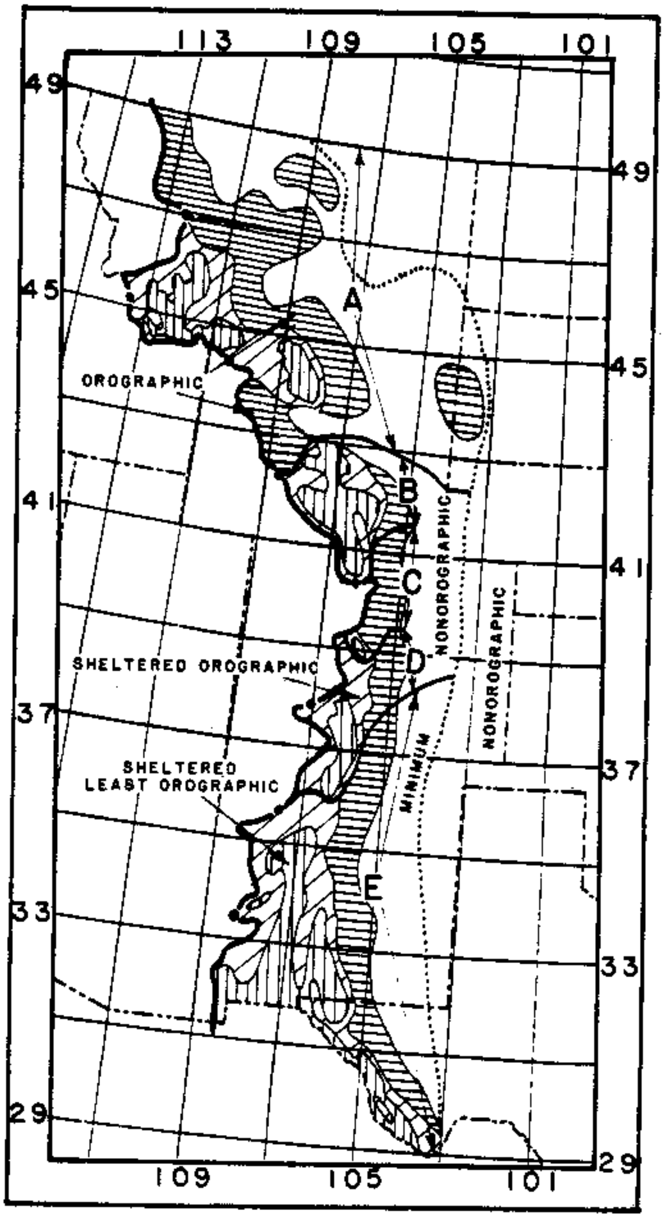


Figure 11.2.--Schematic diagram of subdivision/subregion system used in developing DAD relations.

Table 11.1.--Major river basin subregions within the CD-103 region

Subregion	Drainage
A	Missouri and Yellowstone Rivers
B	North Platte River
C	South Platte River
D	Arkansas River and Upper Rio Grande
E	Pecos and Canadian Rivers and Middle Rio Grande

chapt. 2). However, the wide difference between DAD relations for the Gibson Dam, MT (75), Cherry Creek, CO (47) and Vic Pierce, TX (112) storms brought about the need for intermediate zones. Additional zones were established, therefore, in accord with major drainage boundaries rather than with geographic latitudes. This was done to facilitate the use of the DAD relations. Five zones, called subregions to distinguish them from the terrain related subdivisions of chapter 3, were chosen as listed in table 11.1. These are designated by the letters A to E to simplify notation.

The five subregions are shown in figure 11.1. The boundary between D and E cuts across the Rio Grande near 36°N and across the Arkansas River near 104°W. This was a somewhat arbitrary decision that preserves the limits set for tropical-extratropical storms in chapter 2. In the sense of the development that follows, subregions B, C and D represent transition zones between A and E storm data.

11.3.3 DAD Relations

Figure 11.2 shows the results of combining the subregions of figure 11.1 and the subdivisions of figure 3.2, plus the new minimum nonorographic subdivision. A system of DAD relations was developed to reflect the variations among these 21 subunits. The map of figure 11.2 is intended to give the user a general overview of location of the various subunits. Plate V provides outlines of these subunits on the same scale as the four general-storm PMP maps (plates I-IV). Plate V should be used to determine the appropriate DAD relations to use. Comparable outlines of these same subunits are included as part of the base maps (black background lines) printed on each PMP map.

11.3.3.1 Nonorographic Subdivisions. For the nonorographic zone between the 103rd meridian and the dotted line designating the eastern limit to the minimum nonorographic subdivision, DAD relations developed from HMR No. 51 apply. These relations were based on averages of data along the 103rd Meridian. The use of three such averages is considered adequate, since little variation with latitude occurs in HMR No. 51. The three sets of DAD relations for subregions A, B-D and E, are shown in figures 11.3 to 11.5. In these figures, the 6-, 24-, and 72-hr relations represent averages within the latitudes of the respective regions from HMR No. 51. The 1-hr relations are all the same and were obtained from HMR No. 52.

11.3.3.2 Minimum Nonorographic Subdivision. As stated in section 11.3.1, this subdivision was created to reflect a region where average depth decreases with area at a more rapid rate than indicated by relations for the western border of HMR No. 51. No specific information exists on which to base the magnitude of this accelerated decrease with area size. At smaller area sizes (<500 mi^2), the relations should not differ from those derived for the nonorographic subdivision in section 11.3.3.1. The choice of how the remainder of the relation was shaped required judgment. The adopted curves are roughly 20 percent lower than the nonorographic relations at 2,000 mi^2. The curves (fig. 11.6 to 11.8) have a reversal of curvature to approximate the slope of the nonorographic curves at larger area sizes.

11.3.3.3 Orographic Subdivision. The Gibson Dam, MT (75) storm of 1964 was considered to be the best example for a prototype orographic storm for the Missouri and Yellowstone River Basins. As such, the orographic DAD relations for

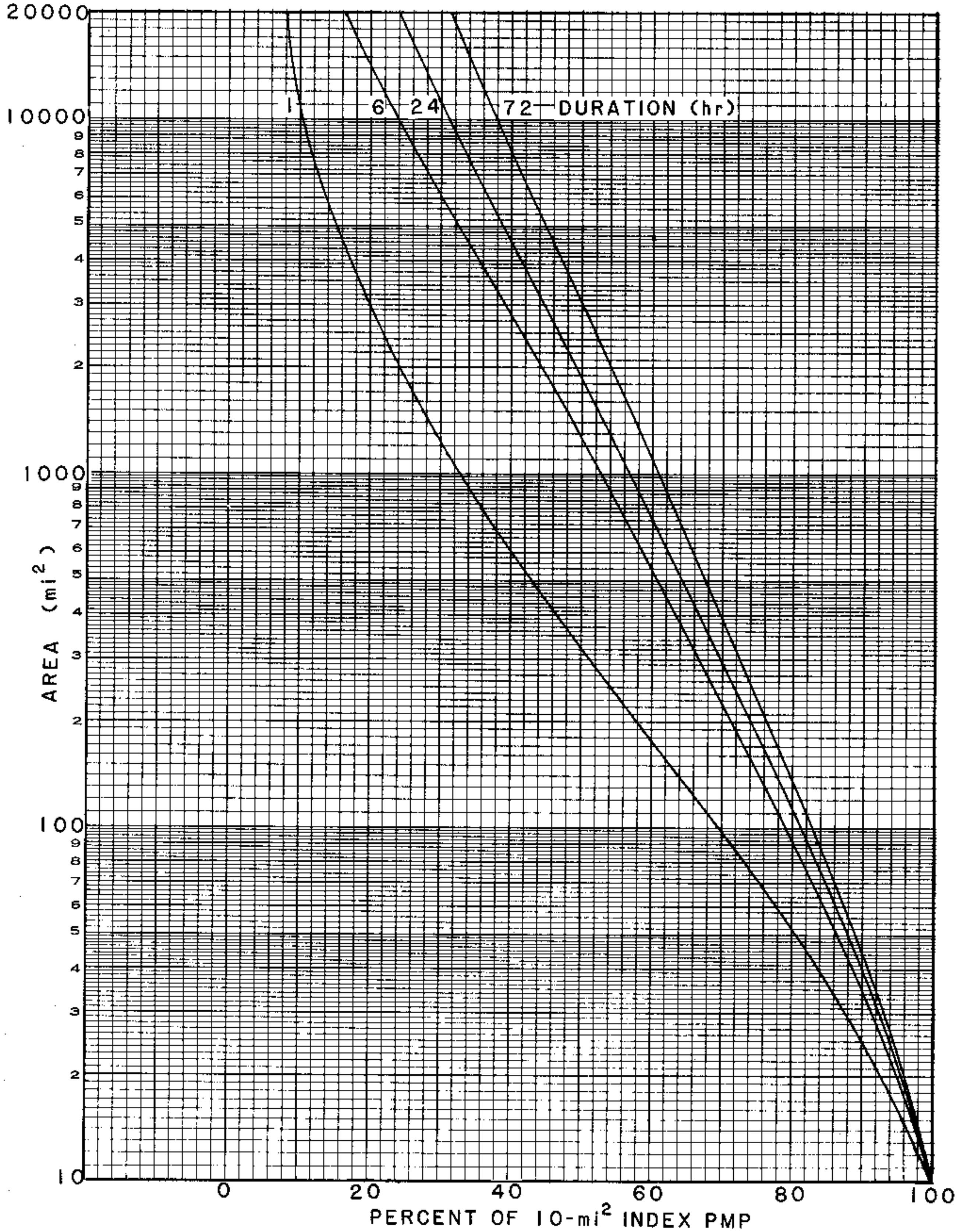


Figure 11.3.--DAD relation, A nonorographic subunit.

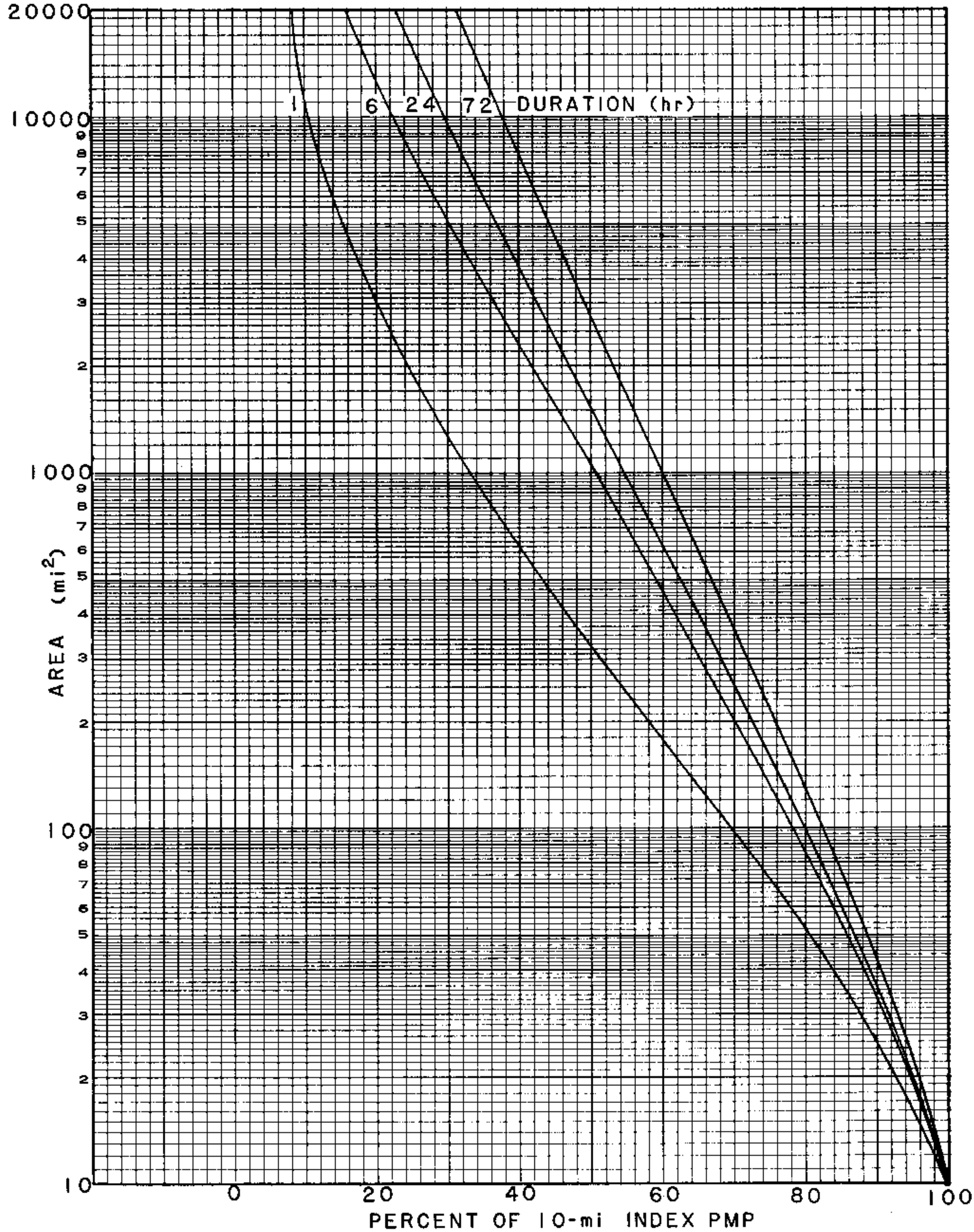


Figure 11.4.--DAD relation, B to D nonorographic subunit.

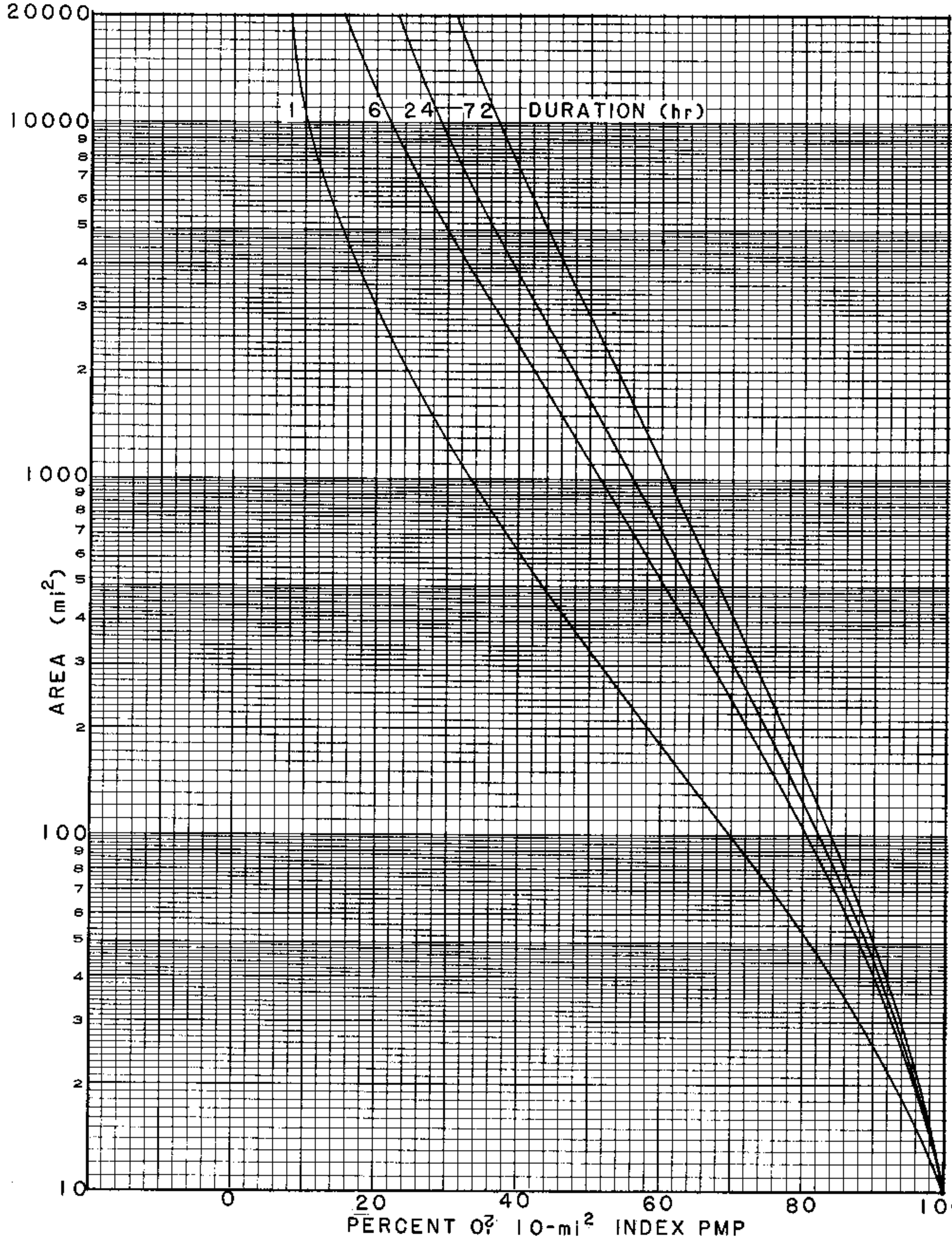


Figure 11.5.--DAD relation, E nonorographic subunit.

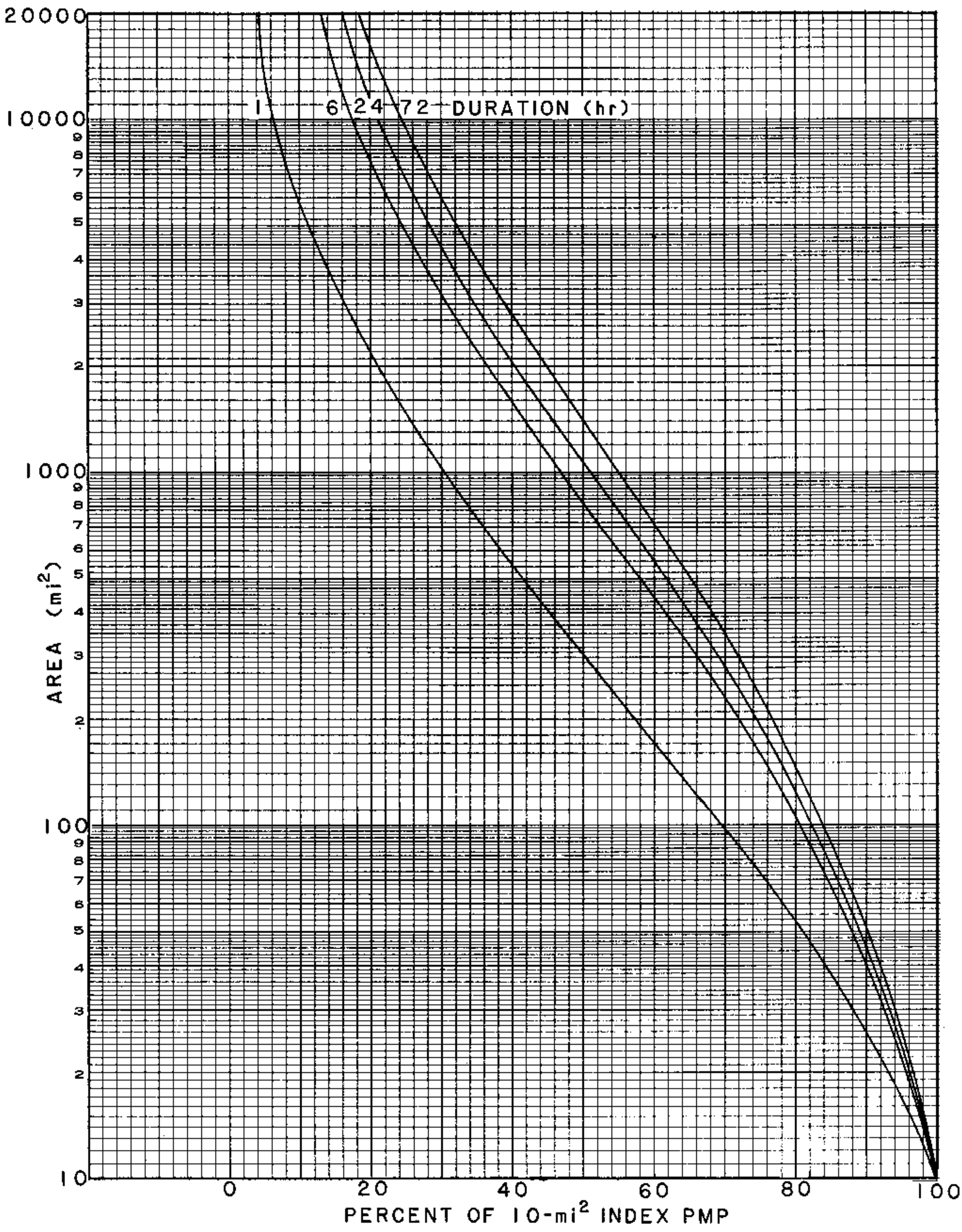


Figure 11.6.—DAD relation, A minimum nonorographic subunit.

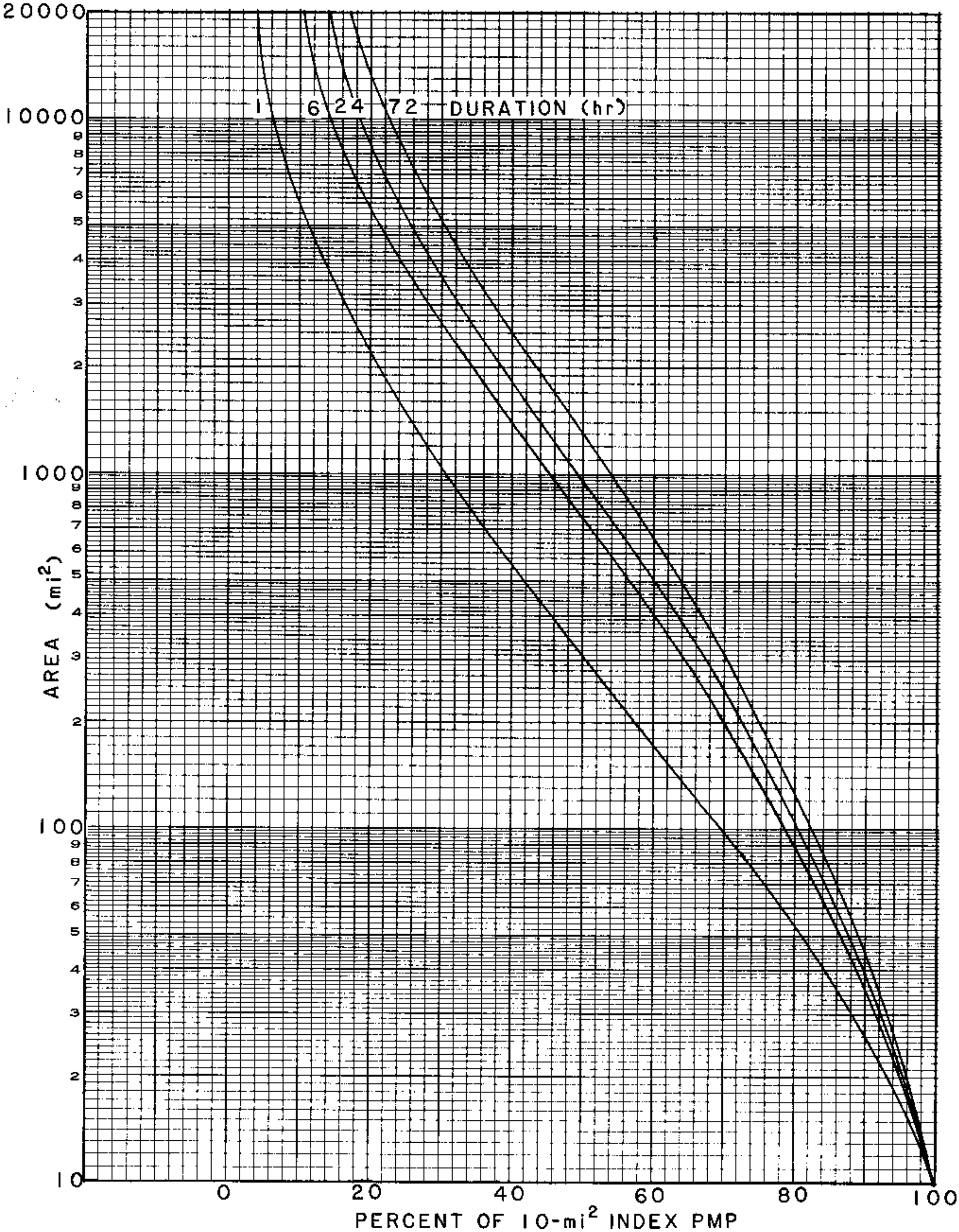


Figure 11.7.—DAD relation, B to D minimum nonorographic subunit.

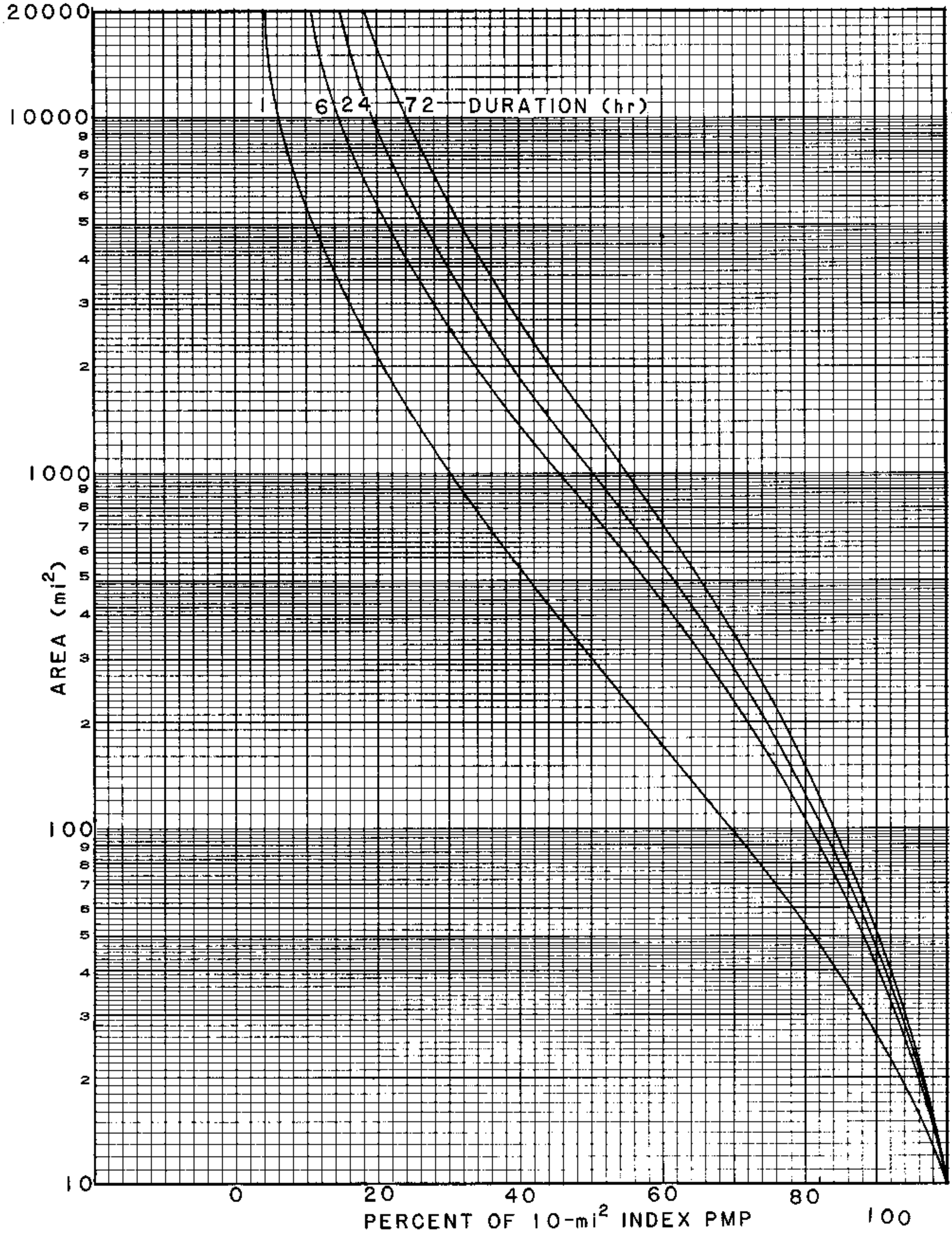


Figure 11.8.—DAD relation, E minimum nonorographic subunit.

the subregion should reflect those found in this storm. The moisture-maximized areal values of this storm were considered as key values that the orographic PMP DAD relations should closely envelop. A trial process was used to develop the set of relations for 1-, 6-, 24-, and 72-hr shown in figure 11.9. The relations show noticeably less fall off with increasing area than shown in the nonorographic and minimum nonorographic relations. They result in close envelopment of the maximized Gibson Dam storm data for areas between 1,000 and 3,000 mi^2. The envelopment is somewhat larger below 1,000 mi^2, but the moisture-maximized amounts are still enveloped by less than 10 percent.

No other major orographic storms in the CD-103 region were of sufficient magnitude to consider in setting the level of DAD relations for this subregion. Therefore, to develop relations for the other orographic subregions, the following question was considered. How should the orographic DAD curves vary toward southern latitudes (subregion E)? Orography should play a significant role at both northern and southern latitudes. However, for the northern latitudes, the likelihood that storms will stagnate, move slowly, or persist in effectiveness is somewhat greater than in the south. In the south, storms are more transient and thus not as effective in producing large areally-averaged precipitation amounts. On this premise, the level of the E orographic subregion relation (at 2,000 mi^2) was set at two-thirds the level of the A subregion that was based on the Gibson Dam storm data.

It was not possible to take a constant fraction of the Gibson Dam relations throughout all area sizes, because this would have resulted in curves that had slopes with greater fall off with area than the nonorographic curves in the smaller area sizes. Orographic relations were developed that give slightly less decrease with area than nonorographic relations at all areas, and somewhat parallel the orographic relations of Gibson Dam at larger areas (>1000 mi^2), as shown in figure 11.10 for subregion E.

These relations were tested against storm data from major storms in the area. Storms at McColleum Ranch (58), Meek (27), Rancho Grande (60), NM and the transposed Vic Pierce, TX (112) storm were all considered. In each case, the orographic relations were sufficient to allow envelopment of the moisture-maximized areal data.

In the absence of other information, the A and E orographic relations were averaged to obtain a set of relations for the C subregion (fig. 11.11). These relations in turn, were tested against such important storms as Big Elk Meadow (77), Fry's Ranch (30), and Ward District (1), CO to ensure that the results enveloped the in-place moisture-maximized amounts at all areas.

Following this pattern, the orographic relations in subregions B and D were obtained from averages of A and C, and C and E data, respectively (fig. 11.12 and 11.13). This process resulted in a system that essentially divided the difference between the A and E orographic relations into five equally spaced relations for each duration. Subregion D relations were evaluated relative to important storms at Penrose, CO (31) and Rociada, NM (8). Maximized data were enveloped at all area sizes. No storm data was available to verify relations for subregion B.

11.3.3.4 Sheltered Least Orographic Subdivision. No analyzed storm data were available for guidance west of the orographic subdivision (sec. 11.3.3.3), limit

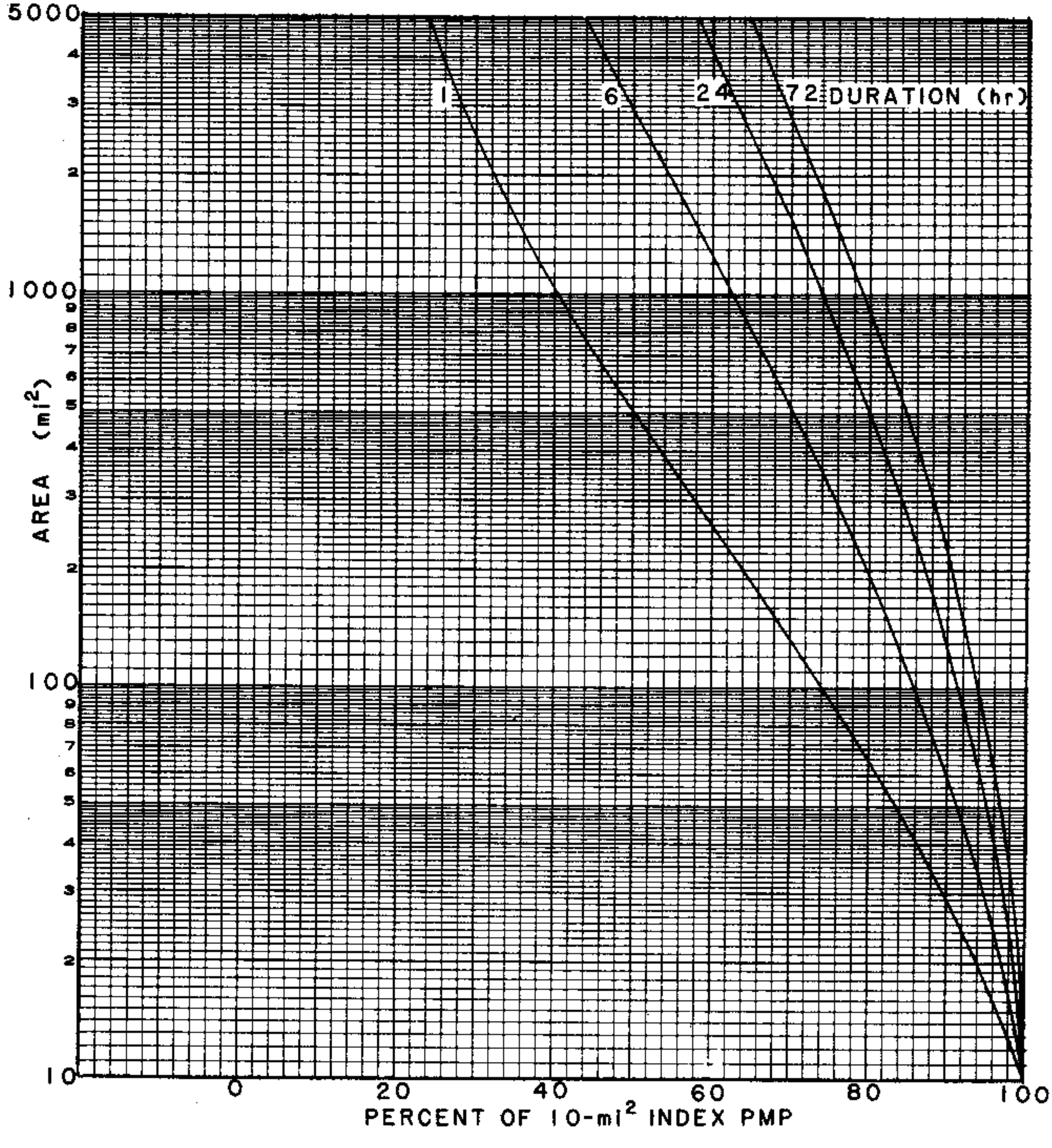


Figure 11.9.--DAD relation, A orographic subunit.

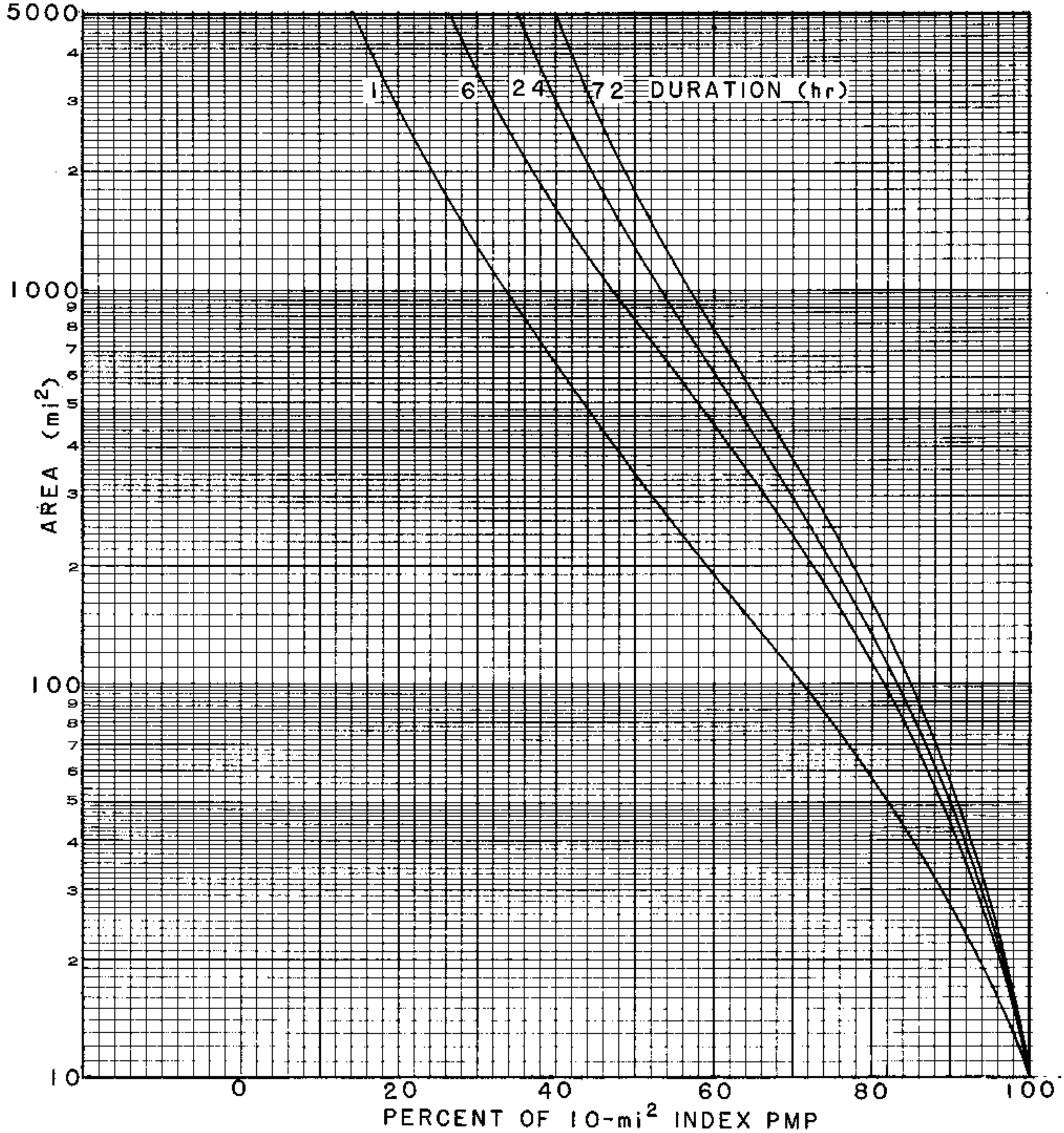


Figure 11.10.--DAD relation, E orographic subunit.

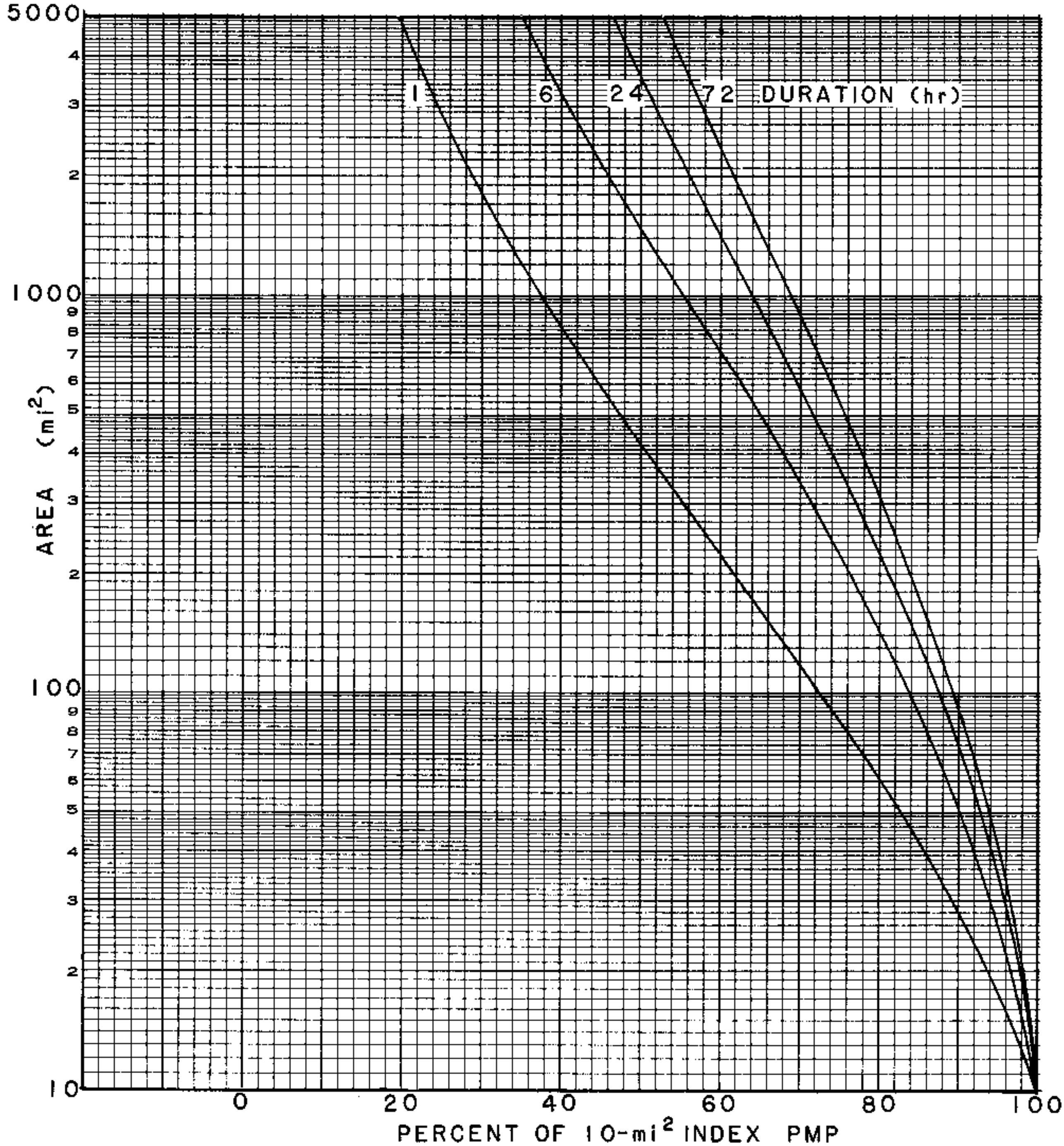


Figure 11.11.--DAD relation, C orographic subunit.

of first upslopes, on which to base DAD relations for the sheltered subdivisions. It was necessary, therefore, to develop a process to relate curves for these subdivisions to the others already developed. For the sheltered least orographic subdivision, the relations should decrease more rapidly than the orographic relations, but perhaps not to the degree of the minimum nonorographic curves. The curves adopted were an average of the minimum nonorographic and orographic relations within the A subregion, and similarly within the E subregion. Subregional averages were then made to get the relations for C, B, and D as was done for the orographic curves. Figures 11.14 to 11.18 show these curves.

11.3.3.5 Sheltered Orographic Subdivision. The relations for this subdivision were developed in a similar manner to those for the sheltered least orographic subdivision in section 11.3.3.4. Averages were made between the orographic and sheltered least orographic relations in subregion A and in subregion E, and then subregional averages of these results were made to obtain relations for subregions C, B, and D. These DAD relations are shown in figures 11.19 to 11.23.

11.4 Comparison With Major Storm Data

In this section, concern is given to how well the depth-area-duration relations described in this chapter compare to the observed moisture-maximized data from major storms. Obviously, it would be easy to develop a set of DAD relations that enveloped all available storm data. Such a result would lead to overly conservative PMP estimates. If, however, the storm sample is reasonably representative of major storms, it is expected that, when moisture maximized, there should be instances where the PMP DAD relations envelop the storm data by 10 percent or less.

The DAD for storms in table 5.3 for which DAD data were available (see Appendix B) were moisture maximized and plotted for 6-, 24- and 72-hr durations. These results were then compared to the results derived from this study, as follows. Isohyetal maps for the respective storms were positioned in place of occurrence over the 10-mi^2 PMP index maps and areal average values determined for selected areas (usually 10, 200, 1,000 and 5,000 mi^2). These areal-averaged 10-mi^2 values were then combined with the DAD relations in this chapter, weighted appropriately, and plotted to give PMP depth-area relations for 6, 24 and 72 hr.

The following comments are given regarding those storms whose maximized areal amounts were considered controlling (closely enveloped).

1. Gibson Dam (75). The 24-hr moisture-maximized depth-area relation was used to define the "A" orographic relation (fig. 11.9) and thereby is enveloped by 10 percent or less for all areas through 5,000 mi^2. At 6 hr, envelopment is 10 percent or less for areas between 400 and 5,000 mi^2. This storm is the only large area storm in the region for which 1-hr data are available, and all moisture-maximized 1-hr values are well enveloped by the 1-hr relation given in figure 11.9.

2. Springbrook (32). At 24 hr, the moisture-maximized data are enveloped by 10 percent or less for areas between 200 and 5,000 mi^2. Envelopment by 10 percent or less occurs at 6 and 72 hr between 400 and 5,000 mi^2 (fig. 11.3).